High intensity metal ion beam production with ECR ion sources at the Lawrence Berkeley National Laboratory

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The large number of different experiments performed at the 88 Inch Cyclotron requires great variety and flexibility in the production of ion beams. This flexibility is provided by the two high performance electron cyclotron resonance (ECR) ion sources, the LBL ECR and the AECR-U, which can produce beams of ions as light as hydrogen and as heavy as uranium. With these two sources, up to six different metals can be preloaded using two types of ovens. The ovens are mounted radially on the ion sources and inject the metal vapor though the open sextupole structure into the plasma chamber. For the superconducting ECR ion source VENUS, which is under construction at Lawrence Berkely National Laboratory, the use of radial ovens is no longer possible, because the magnetic structure is closed radially. Therefore, we are developing two new axial oven types for low and high temperature applications. Metal ion beam production in ECR ion sources using the oven technique is discussed. The design of the axial oven is presented. Finally, the efficiency of the axial oven is compared with the radial oven for the production of Ca. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1425781]

I. INTRODUCTION

The increasing demand for high intensity high charge state heavy ion beams for nuclear and high-energy physics has driven the development of various methods to feed solids into electron cycltron resonance (ECR) ion source plasmas. The most important techniques are (1) evaporation from external furnaces, (2) use of volatile chemical compounds, (3) online chemical synthesis, (4) sputtering, (5) evaporation by vacuum arc or laser beam, and (6) direct insertion.[1] From all these methods mentioned, the oven technique is the least intrusive to produce metal ion beams, especially if pure metals can be used. The production methods at Lawrence Berkeley National Laboratory (LBNL) include the use of gaseous compounds, the oven technique, the direct insertion method, and the metal ions from volatile compounds (MIVOC) method. 41 different metal ion beams from solids have been produced with the Lawrence Berkeley Laboratory (LBL) ECR or the AECR-U ion sources so far. Figure 1 shows the periodic system with all the metals tested in our ion sources so far and Table I shows a few high and medium charge states metal ion beams produced by the LBNL AECR-U.

II. METAL ION BEAM PRODUCTION USING THE OVEN TECHNIQUE

Both the LBL ECR and the AECR-U ion sources are built with radial access. Six radial slots between the sextupole magnet bars provide additional pumping and easy access to the plasma chamber for ovens and feedthoughs. Two types of radial ovens are used at LBNL. The low temperature oven is indirectly heated and can be operated at temperatures up to 650 °C.[2] The high temperature oven consists of a resistance heated Ta or W furnace operating at temperatures up to 2100 °C.[2]

Generally, a metal vapor pressure of about 10^{-3} to 10^{-2} mmHg is required inside the oven (at an oven aperture of about 3 mm diameter) to supply the right amount of atoms to the ECR plasma. The temperature needed to produce a new metal ion beam can be estimated from the vapor pressure curve of the respective metal. Besides the temperature required to evaporate the metal, chemical compatibility of the hot liquid metal and the crucible must be considered.[3] For metals with temperature requirements less than 1600 °C ceramic inserts such as zirconia, alumina, or yttria can be used to prevent alloying of the heating crucible with the molten metal. For higher temperatures, ceramics begin to sublime and cannot be used. The material has to be either loaded

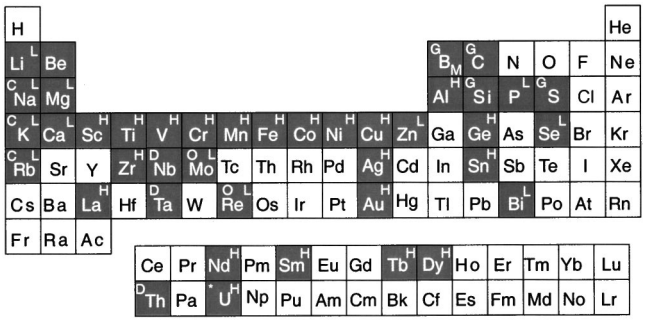

FIG. 1. The periodic system with all the solids tested in our ion sources indicated in gray. H—high Temperature oven, L—low temperature oven, G—gases, M—MIVOC, O—oxides, and C—chemical synthesis, and D—direct insertion.

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TABLE I. A few high and medium charge states metal ion beams produced by the LBNL AECR-U.

Q	^{24}Mg 555 °C	^{40}Ca 590 °C	^{27}Al 1400 °C	^{51}V 1800 °C	^{59}Co 1700 °C	Q	^{197}Au 1450 °C	^{209}Bi 575 °C	^{238}U 1650 °C
6			59			25		70	
7	125		72			26		*	
8	174		73			27		75	
9	148		57			28		60	
10	131		40			29		55.4	
11	20	225	12	80		30	35.5	57	
12	3	175	0.6	90	125	31	33.4	48.4	24.5
13		125			116	32	30	41	24
14		83			97	33	*	32.5	23
15		*			*	34	22.5	25	20
16		25.6			58	35	18,5		16
17		*			63	36	13.5	16	13.3
18		3.1			24	37		11.9	12.7
19		0.25			20	38	9.2	9.4	11.3
20					13.1	39	*	*	9.3
21						40	4.8	5.2	*
22						41	3.2	4.4	5
23					0.8	42	*	*	4
						43	2	3	3.1
						44	1.5	2.2	*
						45	*	*	*
						46	1	1.2	1.8
						47	0.5	0.9	1.4
						48		0.6	1.1

directly into the W or Ta furnace or a special crucible must be used: Chemical compatibility of crucibles for most elements is discussed in Refs. 3 and 4.

If the pure metal is too aggressive (e.g., alkaloids) or the isotope is not available as pure metal, online chemical synthesis can be used (see Fig. 1). For example, alkali metals can be loaded in as alkalichlorides and mixed with calcium. When heated in the low temperature oven CaCl is formed and the pure alkali metal is released into the plasma.[5]

If the temperature required is too high, chemical compounds can be utilized to produce the desired metal ion beam. However, careful consideration should be given when choosing the compound. Oxides, which sublime at lower temperatures, are the best choice for refractory metals since oxygen is an excellent mixing gas to use in the plasma discharge. For example rhenium oxide (Re_2O_7) sublimes sufficiently at temperatures above 140 °C, whereas for the pure metal, 2790 °C is needed to reach a vapor pressure of 10^{-3} mmHg.

Chemical compounds such as fluoride, chlorides, or organic compounds (MIVOC) require very low temperatures or even no heating at all. Their major drawbacks are the impurities (carbon, fluorine, or chlorine), that are released from the compound as well and contaminate the plasma chamber walls. Therefore, the ion source performance and stability can be compromised particularly for long, high intensity applications.

III. HIGH INTENSITY BISMUTH AND ION BEAM EMITTANCE

For the next generation radioactive isotope accelerator (RIA) up to 10 pμA of uranium 30+ will be needed for the heavy ion driver linac.[6] To predict the expected ion beam emittance for heavy ion beams extracted from an ECR ion source for injection into the RIA radio frequency quadrupole (RFQ),[7] ^{209}Bi emittance measurements were performed with the AECR-U. The emittance has been measured over a range of charge states from 21^+ to 41^+ after the AECR-U was optimized on $^{209}Bi^{27+}$ to produce about 1 pμA. Figure 2(a) shows the charge state distribution peaked at 27^+ (30 eμA or 1.1 pμA). Figure 2(b) shows the dependence of the normalized xx' emittance values on the Bi charge state for an unchanged ion source tune. From Fig. 2 it is evident that at these ion beam intensities, the normalized emittance is predominantly dependent on the charge state and not on the current. For instance, the ion beam emittance of 18.8 eμA of Bi^{21+} was measured to be 0.07 π·mm·mrad, while the emittance of 18 eμA of Bi^{32+} was 0.03 π·mm·mrad. This is consistent with the model that high charge state ions are extracted closer to the axis of the ECR ion source plasma.[8,9]

IV. AXIAL OVENS

Two off-axis axial ovens have been developed at the 88 Inch Cyclotron. There are two main motivations for these new oven developments. For the superconducting ECR ion source VENUS, which is now under construction at LBNL,[10] the use of radial ovens is no longer possible, because the magnetic structure is closed radially.

Secondly, for the production of superheavy elements intense metal ion beams of rare isotopes like ^{48}Ca, ^{36}S, or ^{85}Rb are required. Since those isotopes are very expensive, a minimal consumption is desired. As shown by the Dubna group,[11] a hot liner covering the plasma chamber walls can be very

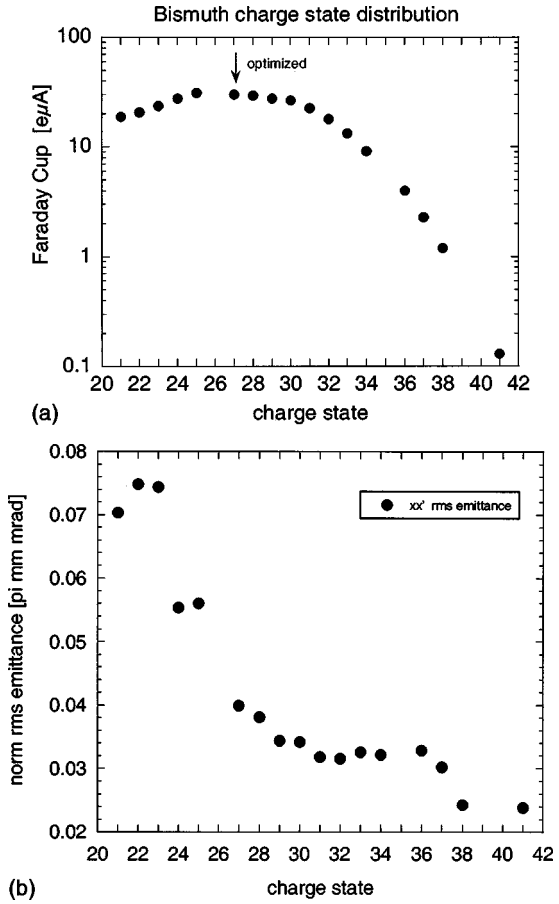

FIG. 2. (a) Bismuth charge state distribution used for the emittance measurements of (b). (b) Dependence of the normalized xx' emittance on the charge state for bismuth.

effective in increasing the overall ion source efficiency. For this purpose, an axial oven is much better suited than a radial one.

If the axial oven is placed on or close to the center of the ion source axis, plasma heating can prevent a precise temperature control at lower temperatures.[9] To decouple the heating of the oven from the plasma, we have decided to insert the oven off-axis between the plasma flutes. At this position, the oven can be inserted up to 5 cm into the plasma chamber without being effected by the plasma. In addition, the off-axis oven does not interfere with the biased disk mounted on axis or with an axial iron plug, which is used to enhance the magnetic field.

A. Miniature high temperature oven

Figure 3(a) shows the mechanical drawing of the new miniature high temperature oven. It is designed to fit though a standard 35 mm ConFlat flange. The oven consists of a resistance heated tantalum or tungsten furnace, which is designed to have the same electrical resistance over the whole geometry to avoid temperature gradients due to changes in electrical resistance. Three layers of Mo heat shields surround the crucible. The outer copper shell and the current leads are water cooled to decouple the oven heating from the plasma. The oven has been tested off line to temperatures up

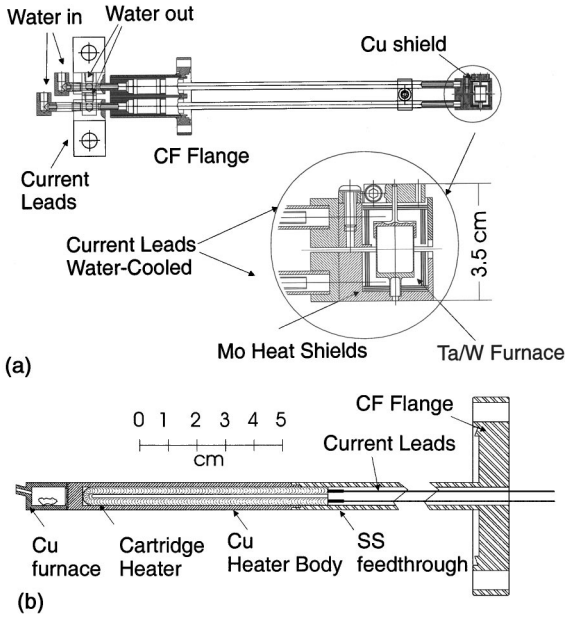

FIG. 3. (a) Mechanical drawing of the new high temperature oven. The current passes through the water-cooled current leads through the furnace and heats it. (b) Mechanical drawing of the low temperature axial oven.

to 2100 °C and in the LBL ECR for the production of titanium. A maximum power of 380W is needed to reach 2100 °C. The same oven design will be used for the VENUS ion source.

B. Miniature axial low temperature oven

Figure 3(b) shows the mechanical drawing of the low temperature axial oven. The demountable copper furnace is fastened to a copper block, which is indirectly heated by a cartridge heater. The oven can be reliably used for temperatures up to 650 °C. A thermocouple is inserted into the heated copper block to monitor the temperature. A proportional temperature-controller unit maintains the temperature variation within less than 0.1%, which is required to assure stable ion beam output. The oven was successfully tested for the production of Mg (120 eμA of Mg^{8+}) and Ca (60 eμA of Ca^{11+}) beams.

V. OVEN EFFICIENCIES

For medium to high intensity ion beams, typical consumption rates for the radial ovens are between 1 and 3 mg/h, resulting in an ionization efficiency into a single charge state of about 0.1% to 0.2% for the high temperature oven and 0.2% to 0.6% for the low temperature oven. These low efficiencies are due to the radial oven geometry, where the vapor has to diffuse through a 6 mm wide and 4 cm deep narrow slit in the water-cooled sextupole housing. Therefore, a major part of the metal condenses on the cold surfaces of this slit channel. If inexpensive metals are used, consumption rates are not critical since the oven crucible volume of about 1 cm^3 is large enough to produce high intensity ion beams for 1 to 2 weeks of continuous operation. However, for high intensity ion beams from rare isotopes (e.g., 10 particleμA of ^{48}Ca), the consumption has to be minimized. By using an

TABLE II. Measured ionization efficiencies for Ca in comparison with results from other groups. The efficiencies given represent the overall system efficiencies (ion source and transport line).

		Charge	Current	Mg/h	efficiency		Time	
LBNL	Ca-40	11	8.9	0.31	0.4%	Radial oven	97 h	
LBNL	Ca-40	11	53	0.6	1.25%	Axial oven	25 h	
LBNL	Ca-40	9	36	0.2	3.1%	Axial oven + hot liner	45 h	
LBNL	Ca-40	8	30	0.2	2.9%	Axial oven +hot liner	45 h	
LBNL	Ca-48	10	48	0.25	3.44%	Axial oven+hot liner	200 h	
DUBNA	Ca-48	5	50	700	2.6% to 3.6%	Dubna Hot screen	Longtime operation	[9] [5]
DUBNA	Ca-48	5	100	600	6%	Dubna Hot screen, CaO+Zr	Test	[5]
JYFL	Ca-40	11	30	0.3	1.4%	Miniature oven	Test	[8]

axial oven as described in Sec. IV B instead of the radial one, the ion source efficiency was improved by a factor of 3 to 4 (see efficiency values in Table II). As a next step, a tantalum-liner was installed inside the plasma chamber. The liner, which is heated by the lost plasma particles and microwave power, minimizes the condensation of metal vapor on the chamber wall. A thermocouple was installed though one of the radial ports to measure the temperature during operation. At a microwave power of 300 W, the liner reached a temperature of 400 °C, which corresponds to a vapor pressure of 10^{-4} mmHg for Ca. With the liner installed, the peak charge state was shifted to 9+ (from 11+), which is still sufficient to reach the required energy of 5 MeV/nucleon with the 88 Inch Cyclotron. An efficiency of about 3.1% was achieved for Ca^{9+} and about 2.9% for Ca^{8+}. After the successful tests with Ca-40, a 200 h experiment using 48 eμA $^{48}Ca^{10+}$ was performed at the 88 Inch Cyclotron. The average Ca-48 consumption was 0.25 mg h, which corresponds to an efficiency of 3.44%. The beam stability was excellent throughout the experiment. Table II shows a comparison of the measured ionization efficiencies with results from other groups.[11–13] With the hot tantalum-liner installed, a total system efficiency of 14% (with all the Ca charge states summed up) was measured after the analyzing magnet. The ion beam transport efficiency though the analyzing section is about 60%. However, for rare gases, a typical ionization efficiency of 60% to 80% has been measured for the AECR-U ion source,[14] which shows there is still room for improvement.

To further improve the ionization efficiency for Ca, we plan to modify the hot Ta liner to allow externally controlled heating or cooling in order to decouple the liner temperature from the ion source plasma tune. Another improvement would be to cover the plasma vessel end plates (extraction plate and biased disk) with a hot liner, too. These surfaces were not covered by the described Ta liner resulting in metal vapor condensation on these surfaces.

ACKNOWLEDGMENT

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